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p-Divisibility of Certain Sets of Bernoulli Numbers

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Abstract. Recently, Ullom has proved an upper bound on the number of Bernoulli numbers in certain sets which are divisible by a given prime. We report on a search for such Bernoulli numbers and primes up to 1000000.

Let $p \geqslant 5$ be prime. Let I be the set of even integers between 2 and $p - 3$. For each positive divisor d of $p - 1$ for which $(p - 1)/d$ is odd, let

$$I(d) = \{2k \in I\colon (2k - 1, p - 1) = (p - 1)/d\},$$

where (a, b) is the GCD of a and b. Then $I(d)$ is the set of $2k$ in I such that $2k - 1$ is of the form $a(p - 1)/d$ with $(a, d) = 1$. Hence, $I(p - 1)$ has cardinality $\phi(p - 1) - 1$, where ϕ is Euler's phi function, and otherwise $I(d)$ has cardinality $\phi(d)$. Also I is the disjoint union of the $I(d)$. Ullom has proved the following theorem concerning the divisibility of Bernoulli numbers B_{2k} by p.

THEOREM (ULLOM [3]). *With p and d as above, the number of* $2k \in I(d)$ *for which p divides* B_{2k} *is less than* $\phi(d)/2 + \phi(d)\log\log p/\log p$.

In this paper, we present numerical data concerning the sharpness of Ullom's inequality. It appears to be far weaker than the truth. See [2] for the relevance of this work to the theory of ideal class groups of cyclotomic fields.

If p divides B_{2k} with $2k$ in $I(d)$, then p divides the relative class number of the unique subfield of the pth cyclotomic field of degree d over the rationals. Thus, the search described below for $2k$ in $I(d)$ with p dividing B_{2k} is actually a search for subfields of the pth cyclotomic field whose relative class number is divisible by p.

We first investigated the triples $(p, 2k, d)$ with $2k \in I(d)$, p dividing B_{2k}, and $p < 125000$. This data was readily available from [4]. It is possible to have as many as five $2k$'s in the same division $I(d)$, as is shown by the example $p = 78233$, $d = p - 1$ in Table 1 of [4]. We have $d = p - 1$ for most of the triples with $p < 125000$. We found two examples of three $2k$'s in the same division $I(d)$ with $d < p - 1$, namely $p = 108877$, $2k = 52498$, 79558, and 81346, $d = 36292$; and $p = 109843$, $2k = 25396$, 27844, and 84202, $d = 36614$.

Obviously, the conclusion of Ullom's theorem is sharper when d is small. The extreme example is $p \equiv 3 \pmod 4$ and $d = 2$, when it gives the well-known corollary

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that p does not divide $B_{(p+1)/2}$. The greatest ratio $(p-1)/d$ which we found for at least two $2k$'s in the same $I(d)$ was 9 for $p = 70489$, $2k = 32932$ and 35272, $d = 7832$.

As reported in [3], we determined all such triples with $p < 125000$ and $d \leqslant 30$. They are (67, 58, 22), (631, 226, 14), (683, 32, 22), (757, 514, 28), (1201, 676, 16), and (12697, 10052, 24). Recently, we searched the following region for such triples:

$$\begin{aligned} 125000 &< p < 140000, & d &\leqslant 20,\\ 140000 &< p < 160000, & d &\leqslant 14,\\ 160000 &< p < 500000, & d &\leqslant 12,\\ 500000 &< p < 600000, & d &\leqslant 8,\\ 600000 &< p < 1000000, & d &\leqslant 6. \end{aligned}$$

We did not find a single new triple in all this computation. This evidence supports Ullom's conjecture that p does not divide B_{2k} for $2k \in I(4) \cup I(6)$.

We tested whether p divides B_{2k} by the methods of [4] with the following simplification. Given p and $2k$, let $c(x, y, z) = x^{p-2k} + y^{p-2k} - z^{p-2k} - 1$. If the coefficients of $B_{2k}/4k$ in the congruences

$$c(2, 5, 6)B_{2k}/4k \equiv (2^{2k-1} + 1) \sum_{p/6<s<p/5} s^{2k-1} - \sum_{3p/10<s<p/3} s^{2k-1} \pmod p,$$

$$c(3, 4, 6)B_{2k}/4k \equiv \sum_{p/6<s<p/4} s^{2k-1} \pmod p,$$

$$c(2, 3, 4)B_{2k}/4k \equiv \sum_{p/4<s<p/3} s^{2k-1} \pmod p,$$

all vanished modulo p, then we did not bother to try the congruence

$$c(4, 5, 8)B_{2k}/4k \equiv \sum_{p/8<s<p/5} s^{2k-1} + \sum_{3p/8<s<2p/5} s^{2k-1} \pmod p$$

because its coefficient must vanish, too. For suppose (with $t = p - 2k$)

$$(1) \qquad 2^t + 5^t - 6^t - 1 \equiv 0 \pmod p,$$

$$(2) \qquad 3^t + 4^t - 6^t - 1 \equiv 0 \pmod p,$$

and

$$(3) \qquad 2^t + 3^t - 4^t - 1 \equiv 0 \pmod p.$$

Adding (2) and (3) gives $(2^t - 2)(3^t - 1) \equiv 0 \pmod p$. We consider the two possible cases $2^t \equiv 2 \pmod p$ and $3^t \equiv 1 \pmod p$, separately. If the first of these congruences holds, then (3) and (1) give $a^t \equiv a \pmod p$ for $a = 2, 3, 4, 5, 6$, and 8, so that

$$(4) \qquad 4^t + 5^t - 8^t - 1 \equiv 0 \pmod p.$$

On the other hand, if $3^t \equiv 1 \pmod{p}$, then (2) and (1) give $a^t \equiv 1 \pmod{p}$ for $a =$ 2, 3, 4, 5, 6, and 8, so that (4) again holds. In the second case, the congruence

$$(5) \qquad (2^{2k-1} + 3^{2k-1} + 6^{2k-1} - 1)B_{2k}/4k \equiv \sum_{0<s<p/6} (p - 6s)^{2k-1} \pmod{p^2}$$

of E. Lehmer [1] was used modulo p. This decides whether p divides B_{2k} because the coefficient of B_{2k} is $2^{-t} + 3^{-t} + 6^{-t} - 1 \equiv 2 \pmod{p}$. However, in the first case this coefficient is

$$2^{-t} + 3^{-t} + 6^{-t} - 1 \equiv \frac{1}{2} + \frac{1}{3} + \frac{1}{6} - 1 \equiv 0 \pmod{p}$$

and (5) modulo p does not work. In this case (5) modulo p^2 did work for every p and $2k$ we tried.

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